研　究　速　報

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Anisotropic Deformation and Strength Properties of Wet-Tamped Sand in Plane Strain Compression at Low Pressures (Part IV)

——On Non-Linearity of Stress-Strain Relation——

低拘束圧下での突き固めた不飽和砂の変形・強度の異方性（IV）

——応力ひずみ関係の非線型性の検討——

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1. INTRODUCTION

In order to perform nonlinear numerical analyses of geotechnical structures, a simplified model for the nonlinear stress-strain relationship of soil is needed. In many cases, the stress-strain relation for soils is modelled by means of various types of hyperbolic equations, which have been used extensively in the finite element analyses of many practical geotechnical applications. The hyperbolic models incorporate two parameters, soil peak shear strength τ_{max} and maximum shear modulus G_{max}. The parameter G_{max} in a monotonic loading (ML) test is commonly determined by extrapolating the stress-strain relation towards zero-strain using a part of data with a range of shear strain γ from, say, about 0.1% to that at the peak. Obviously, the applicability of the model may be properly evaluated only when both G_{max} and τ_{max} are directly measured in a single test. Since such experimental data of the ML tests is very limited, the following aspects have not been fully clarified yet: (i) the physical meaning of the extrapolated G_{max}, and (ii) whether the hyperbolic model can take account the effect of inherent anisotropy. For the first aspect, Shibuya et al. (1991) have recently reported that the hyperbolic fitting was not capable of representing the overall stress-strain relation of various soils and soft rocks and the ratio of the value of E_{max} (maximum Young's modulus) extrapolated using the above-mentioned linear hyperbolic fitting method to the measured E_{max} was not unity for any material examined, particularly 0.1~0.2 for sands.

In this paper, the anisotropic stress-strain behavior of wet-tamped Onahama sand, which was used for the shaking table tests of earthfill dam models (Dong, 1991), is discussed on the basis of the plane strain compression test data, as reported by Dong et al. (1990a, b and 1991a). In these tests, the stiffness was measured in succession for a wide range of shear strain from 10^{-6} to that after the peak.

2. NORMALIZED STRESS-STRAIN RELATIONSHIP

The hyperbolic stress-strain relation using the true values of G_{max} and τ_{max} is expressed in a general form as;

$$\tau=\frac{\gamma}{1/(c_1G_{max})+\gamma/(c_2\tau_{max})} \quad (1)$$

or

$$Y=\frac{X}{1/c_1+X/c_2} \quad (1')$$

where $Y=\tau/\tau_{max}$, $X=\gamma/\gamma_r$ and $\gamma_r=\tau_{max}/G_{max}$. c_1 and c_2 are the coefficients of correction for G_{max} and τ_{max}, respectively, and γ_r stands for the reference strain. In Eqs. (1) and (1'), the relation when $c_1=c_2=1.0$ will herein be called the original hyperbolic equation (OHE). Note that the value of G_{max} was taken as the slope of the initial linear portion, which appeared within the limiting shear strains of about 0.002% (see Figs. 2 and 3 of Dong. et al., 1991a).

The stress-strain relations from the PSC tests of Onahama sand were examined in terms of the normalized stress and strain, Y and X, as shown in Figs. 1 and 2. The secant shear modulus, Y/X, used in Figs. 3 and 4 is equivalent to G_{sec}/G_{max} (c.f., $G_{sec}=\tau/\gamma$). The perfectly-linear material has a constant ratio of $(Y/X)=1.0$ throughout shearing. The proper evaluation of the OHE as a soil model can be made only

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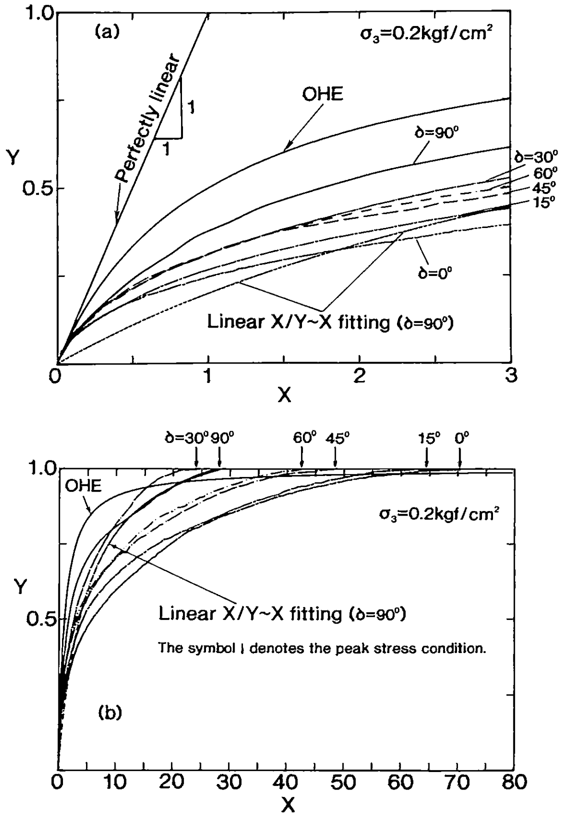

Fig. 1 Hyperbolic relations and observed stress-strain relations, for different angles δ at σ_3= 0.2kgf/cm² in Y~X relation; (a) small strains and (b) large strains

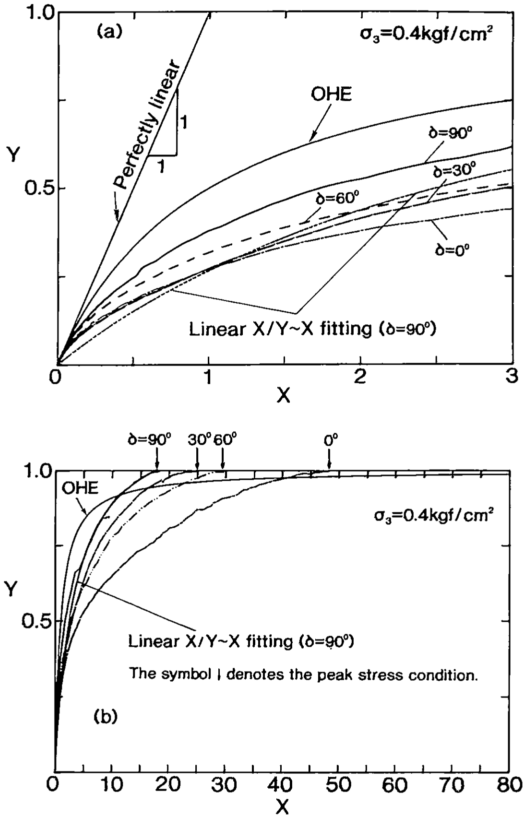

Fig. 2 Hyperbolic relations and observed stress-strain relations for different angles δ at σ_3= 0.4kgf/cm² in Y~X relation; (a) small strains and (b) large strains

when the data is carefully examined both for small strain levels (Figs. 1(a), 2(a), 3 and 4) and for large strain levels (Figs. 1(b) and 2(b)). Note that (i) none of the overall stress-strain relations was properly predicted by using the original hyperbolic equation, (ii) the original hyperbolic equation overestimated the stiffness of the sand at the intermediate strain or stress levels, (iii) the material exhibited different degrees of non-linearity due to the effect of inherent anisotropy. Namely, the degree of non-linearity becomes larger as δ decreases from 90° to 0°.

The results of hyperbolic linear fitting in a plot of X/Y versus X for the case of $\delta=90°$ are shown in Fig. 5, in which the fitted $(G_{max})_{hf}$ and $(\tau_{max})_{hf}$ correspond to the inverse of the intersect at the axis of X=0 and of the inclination of the fitted straight line multiplied by G_{max} and τ_{max}, respectively. The hyperbolic relations for $\delta=90°$ in terms of X and Y (Eq. 1′) with the values of c_1 and c_2 obtained from the linear X/Y~X fitting (Fig. 5) are shown in Figs. 1 through 4. It may be seen that this relation models only the relations at large strains, but fails in simulating the relations at small strains. In particular, the stiffness at small strains is largely underestimated.

3. CONCLUSIONS

1) The original hyperbolic equation, and its modified version in which the parameters were determined from the stress-strain relations at large strains, were found inapproptriate to model the whole range of stress-strain relation from very small to large strain levels of the wet-tamped sand.
2) The inherent anisotropy had a considerable effect on the normalized stress-strain relation; i.e., the

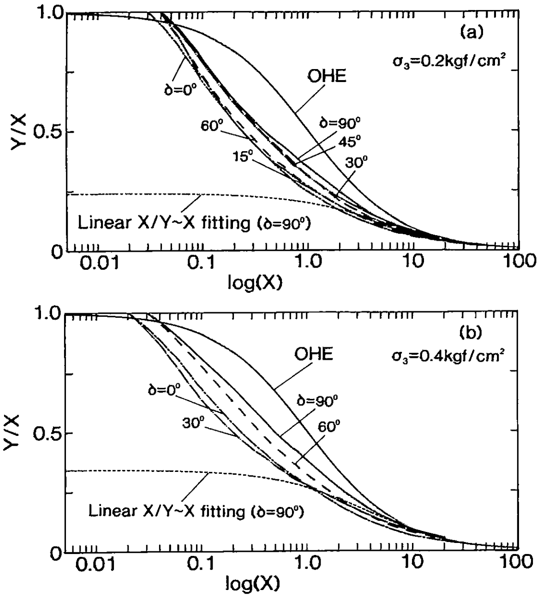

Fig. 3 Hyperbolic relations and observed relations for different angles δ in Y/X~log(X) relation; (a) σ_3=0.2kgf/cm² and (b) 0.4kgf/cm²

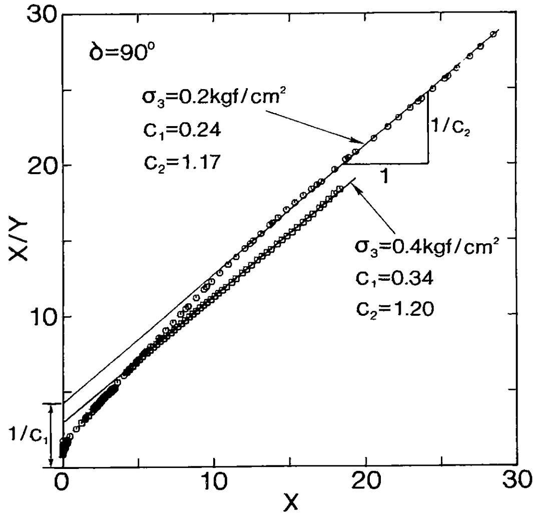

Fig. 5 Results of hyperbolic linear fitting for $\delta=90°$

material exhibited a larger degree of non-linearity with the decrease in the bedding angle δ.

Recently, Tatsuoka and Shibuya (1991a and b) proposed a new model, which is able to model stress-strain curves at both the small and large strain levels. In the next paper, the formulation of the stress-strain relation of the data shown in this paper will be discussed on the basis of the new model.

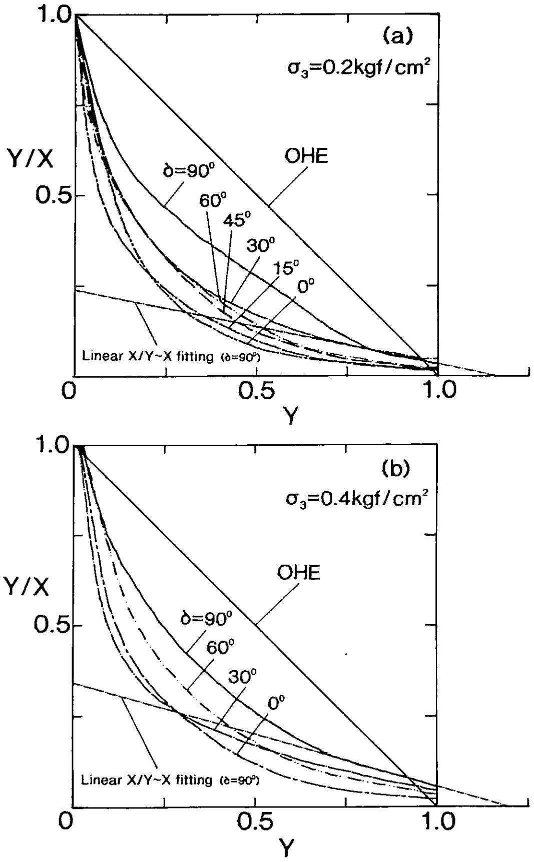

Fig. 4 Hyperbolic relations and observed relations for different angles δ in Y/X~Y relation; (a) σ_3=0.2kgf/cm² and (b) 0.4kgf/cm²

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